Report on the WMO First Workshop on the Coordinated Global Greenhouse Gas Monitoring Infrastructure

10 - 12 May 2022, Geneva, Switzerland

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Introduction

In order to monitor climate change and assist in mitigation efforts in support of the COP-21 Paris Agreement and COP-26 pledges, systematic observation of greenhouse gases (GHGs) and other factors affecting the carbon budget, as well as integration of the output data into global models of the carbon cycle, will be required. Currently, most of the overall GHG monitoring efforts undertaken globally rely heavily on research capabilities and research funding, both in terms of observations and modelling, and therefore sustained global monitoring on a routine daily or even weekly basis is difficult to achieve. Given the increasing focus on the role of GHGs as a driver of climate change and their central role in mitigation steps, WMO convened this Workshop in order to explore the interest of the carbon monitoring community in transitioning relevant activities into an international collaborative operational framework**.**

Opening of the Meeting

Petteri Taalas, WMO Secretary-General, opened the meeting and welcomed participants to Geneva, expressing his desire to hear their perspectives and guidance. He summarized the status of the global climate, noting that lack of action on climate poses one of the largest risks to the future global economy. He described both the continued growth in GHG emissions and concentrations, and the persistence of significant areas of scientific uncertainty about the global carbon budget. These factors point to a need to combine existing research-based observations, satellite data, modelling and data assimilation capabilities into an integrated, internationally coordinated global GHG monitoring system. Most of the required technology already exists: In addition to extensive in situ observation networks, three countries – US, Japan and China – already have carbon-dioxide (CO_2) observing satellites, and Japan and Europe have methane (CH4) observing satellites. Europe will launch a much more ambitious, operational GHG constellation in 2025. High-level political support exists within the UNFCCC and the broader UN system for such a system, and WMO is fully committed to further developing this area. This workshop would be an important opportunity to get input from the carbon monitoring community.

Stephen Briggs, Cambridge University Centre for AI and Environmental Risk and Reading University Department of Meteorology, and Facilitor of the workshop, spoke next. He thanked WMO for its leadership in taking the initiative to convene the discussion on this important and extremely complicated task. Technically, this work involves entering a new and even more difficult domain of Earth system modelling, in which we will need to account for not just what is occurring within the atmosphere itself, but also how the GHGs enter and exit it. Organizationally, WMO provides a model of what can be done, with the World Weather Watch Programme (WWW) and Numerical Weather Prediction (NWP), as well as a series of programmes that can be built on. It is challenging but worthwhile to develop recommendations on what new work could be undertaken within the WMO framework to address this, as well as recommendations concerning the work to be done elsewhere, and how this complex problem could be managed and coordinated internationally, as it will be beyond the capabilities of any individual agency. The Final Report from this workshop will not just provide guidance to the WMO and its Executive Council but also will allow other bodies to consider their roles going forward.

Lars Peter Riishojgaard, WMO Infrastructure Department, next described the structure of the three-day workshop. Each of the first two mornings would consist of presentations. During the first afternoon, participants would split into three breakout groups. The results of the breakout groups were to be considered during the second afternoon, and further refined on the third day, in order to provide the final recommendations from the workshop.

Need for Quantitative Data for IPCC and the Paris Agreement

Han Dolman, GCOS (Global Climate Observing System) Steering Committee, explained the need for additional quantitative data to meet the needs of both the IPCC and the Paris Agreement. A series of analyses starting in the 1980s have shown that a coherent assimilation framework integrating anthropogenic and ecological carbon cycles is essential for effective analysis to meet several outstanding requirements, including:

- Detection of hot spots;
- Monitoring the emissions of hot spots;
- Assessing emission changes against local reduction targets;
- Assessing the national emissions and changes with 5-year time steps.

The natural carbon cycle is extremely complex and involves fluxes that are substantially larger than those associated with anthropogenic emissions; therefore, the net impact of anthropogenic emissions can only be assessed in the context of the whole carbon system. Developing such an integrated framework will be even more complex than NWP. But it is important to do so, as since the magnitude of the anthropogenic emissions is smaller than even the interannual variability of some of the terms in the natural cycle, which makes it difficult to assess what is actually happening in terms of sinks and sources. Substantial increases in in-situ and satellite observations of fluxes and stocks, as well as improvements in land models, both will play key roles in developing the improved framework and analysis.

During the subsequent discussion, it was noted that, while more work clearly is needed, many of the analyses Dolman noted from prior decades have been followed up on through CEOS and other coordination bodies, and that improvements are already underway.

Monitoring the Carbon Cycle

Philippe Ciais, Institut Pierre-Simon Laplace (IPSL), France, outlined a roadmap to move towards a near real-time (NRT) updates of global GHG budgets, based on atmospheric and other observations, via delivery of frequently updated estimates of emissions and removals for each country and key sectors. This NRT project has been developed and implemented by a coalition of universities and research organizations from Europe, China and the US. It may be useful in pursuing an improved monitoring infrastructure in several ways.

The fact that global GHG budgets are established on annual or even longer timescales can help to explain significant inconsistencies between UNFCCC inventories and the latest atmospheric inversion model results. NRT data products have the potential to be important in reconciling such inconsistencies and therefore could play a substantial role in a future global monitoring infrastructure.

This NRT project takes advantage of new estimates of fossil emissions areas in NRT, plus new quarterly global inversions of carbon dioxide and methane fluxes, combined with attribution of top-down flux anomalies using bottom up information. These new data enable near-real time monitoring of carbon emissions, more targeted monitoring of methane ultra-emitters, and NRT fossil methane estimates for extraction basins. The project plans to leverage such observation-based data into national assessments of emissions and sinks at four-month intervals; as well as to attribute national budgets into components; provide NRT estimates of carbon from fires and other extreme events; etc. This would dramatically boost the ability of modelling processes to provide complementary information not available directly from observations.

The ensuing discussion explored sub-annual/NRT budgets and how they might fit within this scoping exercise. NRT/sub-annual GHG analysis requires different infrastructure and activities – and allocation of resources – compared to annual-to- five-year GHG budgets. They might be useful to provide incremental updates to countries on their Nationally Defined Contributions (NDCs), allowing them to more actively design and manage their mitigation activities. In addition, NRT analysis may be very important both to allow attribution of emissions and mitigation, and in order to exploit the power of data assimilation, which provides a more comprehensive picture of what the atmosphere is doing at any given time. On the other hand, accuracy and precision in the context of GHGs is very important, and the required data processing takes more time. However, it may not be either/or; weather prediction has shown that it is well possible to use the same measurements for different purposes with different timeliness requirements – first in original form for real-time NWP, and later for climate reference purposes once the quality control and calibration processes have been completed.

The importance of real-time data exchange of observations was highlighted, both in terms of the value of the output, and its role in helping to catch calibration drift for both space-based and surface-based observing systems. If such issues are discovered only years after the measurements took place, the data records will be irrevocably lost.

The Global Atmosphere Watch

The Chair of the WMO Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee, Greg Carmichael, provided an overview of the Global Atmospheric Watch programme (GAW). Carmichael reviewed its decades of international leadership in advancing science, addressing technical aspects of the research infrastructure, and facilitating the translation of science to services. GAW provides quality assurance and quality control, as well as data and metadata management, support of modelling infrastructure, network design and evolution, as well as a network of experts. With regards to services, GAW uses largely research-based observations from partnerships involving over 100 countries to help deliver integrated products and services related to atmospheric composition of relevance to society in a variety of sectors and fora.

A Global GHG/Carbon Monitoring Framework

Lars Peter Riishojgaard, WMO Secretariat, presented on one potential way forward toward using routine operational GHG monitoring to strengthen the scientific basis for mitigation under the Paris Agreement.

Using as an example the WMO World Weather Watch Programme (WWW) from the 1960s and 1970s, states and organizations could take an integrated, internationally coordinated approach to network design, operation and use of observations. This integrated approach would allow them to leverage resources and work more efficiently towards several critical leaps in the scientific output of modelling and analysis. A coordinated framework could facilitate both time-continuous, global model estimates of GHG concentrations, and systematic records of discrepancies between all observations and respective model priors. The latter would be extremely helpful in supporting direct sources and sinks estimation, and could also be used to support development and improvement of modelling of sources and sinks.

Meeting participants observed that building coordination between the multitude of existing observation networks, large and small, which WMO has advocated through the WMO Integrated Global Observing System (WIGOS), would play a critical role in establishing an integrated Earth system approach including carbon and other greenhouse gases. Furthermore, they noted that such an approach is particularly relevant to GHG monitoring, which requires a comprehensive view of atmosphere, land surface, ocean and vegetation, among other factors. Some of the necessary observations will not come from NMHSs; it is recommended to take advantage of links available via the WMO

Research Board and other coordination mechanisms (such as GCOS, CEOS, GEO) to help bring them in. WMO performance and coordination skills could be extremely useful.

It was noted that international coordination would not eliminate the desire by various states to have their own sources of information; however, common access to observational data, development of common metrics and other elements of a common international infrastructure could be instrumental in avoiding fragmentation in observations, modelling, scientific findings, and ultimately policy positions.

US Sustained Integrated GHG Measurement System

Colm Sweeney, NOAA Global Monitoring Laboratory, summarized the US GHG monitoring system, using that experience as the basis to call for supporting the Paris Agreement with an integrated and sustained, multi-platform, surface-to-space GHG observing system capable of tracking ecosystem, ocean and anthropogenic emissions and removals to improve climate predictions and support mitigation efforts. He echoed the remarks of earlier speakers that tracking anthropogenic emissions alone is insufficient; and argued that "top down" and "bottom-up" approaches in fact are both needed, in tandem, to track GHG emissions and removals at varying time and size scales, and thus in order to provide the information needed by policymakers. Currently, neither type of analysis can go it alone. Currently, systematic errors in carbon dioxide and methane satellite datasets are larger than key ecosystem and anthropogenic flux signals. Stability capabilities aimed at diagnosing processes and tracking emissions cannot be fully exploited without a significantly expanded and sustained GHG reference network of well-calibrated in situ measurements with sufficient density and frequency to reliably correct regional, time-dependent, and cross-platform biases.

Sweeney further supported the notion of leveraging and extending existing WMO programs, namely GAW and the WMO Integrated Global Greenhouse Gas Information System (IG3IS) effort, as part of building and maintaining a continuum from research to sustained operations so as to ensure measurement compatibility over decades while allowing for innovation.

The Workshop participants discussed how the US might proceed towards its goal of providing an operational carbon monitoring system within the next five years, noting that Copernicus might provide some examples/best practices of how to structure such a system, with the involvement of multiple stakeholders. The US is making progress toward integrating top-down observations into the national inventory, but much remains to be done.

Global Carbon Project

Joseph (Pep) Canadell, Executive Director of the Global Carbon Project (GCP), briefed attendees on the defining characteristics of the GCP, and explained its value to the Global Stocktake of the Paris Agreement (Global Stocktake) and in the development of different IPCC socioeconomic pathways.

The Global Stocktake is an iterative process for assessing the implementation of the Paris Agreement and its long-term goals of emission reductions (Article 14, Paris Agreement). The First Global Stocktake, currently underway, is comprised of three processes – information collection and preparation, technical assessment, and consideration of outputs – and is scheduled to be completed in 2023.

The GCP works to provide integrated knowledge of greenhouse gases for human activities and the Earth system. To do so, it leads a large consortium of research organizations to develop annual Global Budgets for for three dominant greenhouse gases — carbon dioxide, methane, and nitrous oxide. It then contrasts and tries to reconcile bottom-up GHG budgets with top-down budgets from atmospheric inversions — and complementary efforts in urban, regional, cumulative, and negative emissions. It benchmarks the multiple existing GHG models against observations.

The ensuing discussion focused on how to improve reliance on use of models for this effort where they are less robust (interannual variability, land/ocean, land/atmosphere and atmosphere/ocean exchange). Canadell said they are systematically identifying priorities for increased observations each year.

Land Surface Modelling

Stephen Sitch, University of Exeter, reviewed the current state of land biosphere models and their role in the analyses of anthropogenic carbon emissions. Sitch acknowledged the diversity of models pertaining to the land biosphere, including land surface models, biogeochemistry models, biogeography models, and forest gap models. He then summarized the development and use of the Trendy ensemble land-surface model (LSM), which for the past 11 years has run a coupled series of Dynamic Global Vegetation Models (DGVMs). Trendy not only generates annual land–atmosphere flux and land-use flux estimates for the Global Carbon Budgets, it also attributes regional carbon fluxes to processes and supports developing regional NRT budgeting efforts.

Sitch noted the great interest generally in consolidated global observation-based benchmarking datasets, and posited that WMO coordination would be useful to help fill key data gaps.

The discussion explored the gaps in knowledge around carbon fertilization and the dynamics of land sinks, as well as the ability of land surface models to represent non-linear processes intrinsic to extreme events (drought good, heatwaves slightly less developed).

Permafrost Carbon Feedback

Claire Treat, Alfred Wegener Institute, presented on historic and current carbon dioxide and methane flux measurements in permafrost regions. The permafrost region in the Arctic holds most of the global inventory of soil carbon, and this may be released either as carbon dioxide or methane. It is difficult, however, to gather adequate observations to integrate permafrost carbon into existing carbon-climate feedback models – the area is remote and temperatures are extreme; satellite UV, visible and near-IR instruments cannot measure in the absence of sunlight; and while airborne measurements can help, not many actually have the ability to trace fluxes. The distribution of active carbon flux measurement sites tends to reflect the financial resources of the local funding agencies rather than any scientific requirements for flux measurements. The potential carbon source strength of the permafrost area remains an open question.

Breakout Groups

For the afternoon of Day 1, in-person participants broke into three groups. Moderators circulated among the breakout groups to lead discussion and record responses on three questions:

(1) *System architecture*: What are the main long-term goals to strive for? What should be the initial priority areas? Strengthening the observing networks, enhanced data sharing for observational data, collaboration on modelling and data assimilation algorithms, estimation of sources and sinks, coupled modelling, or something else?
(2) *Governance*: What level of (technical) coordination are we envisaging? How do we interface with/integrate existing coordination entities? What role of WMO and its governance structure would be most helpful for the overall effort?
(3) *Next steps*: Consolidated requirements for an integrated (surface- and space-based) observing systems? What types of activities would help us get there? Potential pilot/demonstration activities? Engagement with key stakeholders not represented at this workshop?

Key points and conclusions from the discussions were compiled by rapporteurs, presented and discussed during the afternoon of the second day, and then refined on the third day and via follow-on correspondence with the participants to provide final recommendations from the workshop.

Need for Action: Enabling a Global Goal on Observation for the Paris Agreement

Day Two began with a presentation by Joanna Post from the UNFCCC Secretariat, in which she called for a more systematic approach to observation to support the Paris Agreement. She noted that increasing ambitions to mitigate greenhouse gas emissions at global national and subnational levels are intensifying the need to measure GHG concentrations accurately on multiple geographic and time scales. While acknowledging the challenges in coordinating among the substantial list of international and national entities involved in the full observation value chain, Post highlighted the possibilities to further these ambitions via the adoption of a Global Goal on Observation by the Parties, potentially to be discussed at COP 27. She suggested that a more quantitative, observation-enabled information basis would make it substantially easier for Parties to the Convention to make mitigation and adaptation decisions.

The discussion centred on refining the idea of a global goal for observation, noting the importance of adding “timely availability of information” as part of the global goal on observations. It was suggested that observing programs and observing systems should be developed with the explicit recognition of their critical role in underpinning long-term policy developments, rather than serving only research needs that in principle tend to be time limited.

Ocean Data for a Global Greenhouse Gas Monitoring Infrastructure

Mike Smit, Canadian Integrated Ocean Observing System (CIOOS), discussed the important role that the oceans play in the carbon cycle, particularly as a carbon reservoir, and the high uncertainty currently both around key elements of the ocean cycle and regarding the extent to which ocean carbon absorption will continue to scale with increases in atmospheric carbon. What is missing particularly includes understanding of land-sea interactions and biological carbon pumps, as well as sustained observations of decadal processes. Additionally, large gaps exist in observations/data around coastal areas, marginal seas, the Southern hemisphere, and the Arctic; and there is a growing gap between models and observations. In terms of solutions, Smit called for a sustained global ocean observing system and, in particular, a dramatic increase in frequency and density of observations for existing carbon sinks.

The discussion centred on how to establish detailed and robust requirements for the missing elements, with participants calling for a better monitoring system for carbon sinks with more sensors and a way to upscale it, as well as a means to communicate the data and findings to the world. The UNFCCC Secretariat noted the mandate to strengthen link to ocean activities in COP-related work, and made a plea for meeting participants to put down in writing exactly what the needed improvements looked like as part of the outcomes of the workshop.

Greenhouse Gas Monitoring Project at NIES

Akihito Ito, Japan National Institute for Environmental Studies, described Japan’s GHG monitoring activities via the SII-8 Project. SII-8 is a comprehensive study on Multi-scale Monitoring and Modeling of Greenhouse Gas Budgets in the Asia-Pacific region which supports the Global Stocktake. It is funded from April 2021 to March 2024 by the Japanese Environment Ministry.

Like the ongoing initiatives ongoing in the US and Europe described on Day One, SII-8 approaches GHG assessment and monitoring by combining top-down (inverse estimation from atmospheric observations) and bottom-up (accumulation of individual sources and sinks) approaches to develop estimates of urban, national, regional, and global budgets for GHGs. Recognizing the importance of NRT reporting, SII-8 has also provided "quick reporting" on less than decadal time scales up to 2020. Further data accumulation and model analyses through international collaboration are needed to improve accuracy.

Advancing Surface-Based Observational Capabilities

Looking ahead, Lars Peter Riishojgaard, WMO, outlined one possible avenue towards strengthening the observing capabilities needed for GHG monitoring – the WMO Global Basic Observing Network (GBON). GBON combines a commitment by Member countries to systematically improve surface observations with the availability of corresponding financial and technical support through the Systematic Observations Financing Facility (SOFF) for implementation in LDCs and SIDS to correct for persistent shortfalls in capacity in some of the most resource-constrained areas.

Almost all weather and climate monitoring and prediction relies on a production chain that starts with taking observations nation-by-nation around the globe, then exchanging them internationally so the observations can be assimilated into global Numerical Weather Prediction (NWP) models. Facilitating this global exchange and collaboration is one of the main reasons WMO was created.

Currently there are gaps in required observational data coverage for large swaths of the world. It is notable that the majority of these gaps correspond closely to countries with low GDP relative to geographic size (such as LDCs, SIDS). Simply put, these countries are poorly positioned to finance the necessary observational infrastructure.

WMO Members have responded by establishing GBON, which entails a regulatory commitment of all WMO Members to acquire and transmit in real time certain observations at fixed minimum horizontal density and at fixed minimum time frequency. For LDCs and SIDS, both the implementation necessary infrastructure to meet this commitment and the subsequent costs associated with operating and maintaining the system will be supported by a technical and financial support program, the SOFF.

Participants discussed paths by which this model might extend beyond meteorological observations, such as replicating these mechanisms for GHGs, or simply expanding GBON to include GHG observations.

China Satellite-based GHG/Carbon Monitoring Activities

Xhingying Zhang, Deputy Director of the Department for Science, Technology, and Climate Change, and of the National Satellite Meteorological Center, CMA, reviewed China's monitoring of GHGs via five different Chinese satellites launched between 2016 and 2022 – three in the research and development programme, two in operations – illustrating the rapid development of GHG monitoring and mapping via satellite in China.

Zhang described CMA's progress in developing and refining GHG flux mapping nationally and globally using the satellite measurements, verified both against each other and against surface-based observations. The newest satellite, launched 16 April 2022, is pioneering the use of the Aerosol and Carbon Detection Lidar (ACDL)； the first space-borne integrated path differential absorption (IPDA) lidar. Additional satellites are either in planning stages or being discussed. CMA also is working on expanding its surface-based observing network, and is currently constructing about 60 new stations for GHGs measurement.

The discussion focused on the interest in open international data sharing of China's GHG observations, and on technologies used for profile measurements.

Challenges for Operational Greenhouse Gas Monitoring – The Swiss Perspective

Martin Steinbacher, Swiss Federal Laboratories for Materials Science and Technology (Empa), briefed participants on the GHG activities of Empa in Switzerland. Empa's experience provides a successful example of integrating operational observations with the traditional inventory process to provide improved GHG monitoring and reporting.

Switzerland plays an active role in supporting GAW worldwide. Empa has provided one of the GAW Quality Assurance centres for more than 20 years, and provides long-term training and support for ground-based observations in the developing world. Its experience has shown that there can be substantial barriers to the start-up of GHG emissions tracking, as even willing countries commonly lack the expertise and infrastructure needed for quality tracking. Ten or more years of support is often needed. Start-up equipment costs average from 100,000-500,000 Euros.

Empa also provides continuous GHG observations to contribute to the national inventory of emissions in Switzerland. Like most European countries, while CO2 accounts for the most significant GHG emissions, the uncertainties associated with methane and N2O emissions are significantly higher. The combined inventory for 2013-2020 uses a top-down approach to substantially reduce uncertainty for both of these (comparted to the bottom-up inventory results, which are compiled by another federal agency, the Swiss Federal Office of the Environment, or FOEN), and to track where emissions are underreported and overreported, as well as review seasonal variations. Verification is undertaken via a collaborative process between Empa and FOEN, which works well, in part because Switzerland is a small country where experts often know each other and can meet easily.

The discussion centred on interface with the inventory community. Participants described Switzerland as one of the relatively few countries where the observations are successfully integrated. Extending this practice to a significantly larger number of Members will be a huge challenge for WMO, and early adopters like Switzerland and New Zealand will be invaluable to show the way. The advice was to start slowly and to frame the observations as "supporting" rather than on "verifying" the inventory. It was also observed that European projects that deal with these questions – notably Copernicus – already have been establishing contacts in the inventory community. This had been found to be difficult initially, because the two communities often speak different languages, but Copernicus had now made considerable progress, and is currently prioritizing the institutionalization of that contact. It was noted that GHG observations will have other users as well – cities and investment companies would like to make use of them, assuming the system can accommodate them.

Copernicus Atmospheric Monitoring Services (CAMS)

Vincent-Henri Peuch, ECMWF, discussed the Copernicus Atmospheric Monitoring Services (CAMS) and its Carbon Verification and Support Capacity, which provides another model for how systematic observations can be used to advance GHG monitoring. Copernicus is part of the EU Space programme, managed by EC DG DEFIS (Defense Industry and Space). It has three components: space (the Sentinel satellite series), in situ (mainly relying on subsidiarity), and services (organized along six themes). CAMS provides two of the six Copernicus services – namely, open and free information products based on Earth Observation about past, current and near-future (forecasts) global atmospheric composition; and emissions and surface fluxes of key pollutants and greenhouse gases.

Backed by high-level policy and law (the EU Green Deal and the European Climate Law of 2021), CAMS makes available a robust selection of products around ECVs: monitoring, analyses and forecasts, detecting anomalies in methane, re-analyses, expansion of existing inventories with supplementary data, and inversions. Looking forward, CAMS is working to develop by 2026 the larger vision of an integrated operational system of prior information (inventory) and observations serving all users.

National inventory agencies help co-design CAMS products and plans: expert users from the inventory agencies work closely with Copernicus to develop the products and support the observation-based monitoring.

Data Assimilation for Carbon Monitoring

Brad Weir, NASA Goddard Space Flight Center, presented results from the OCO-2/GEOS L3 model analysis of carbon anomalies during Covid in Spring 2020, and used them to highlight urgent, outstanding needs in both observations and biospheric models that must be addressed to allow reliable analysis of GHG mitigation activities.

Weir made the case that that current modelling science places too much emphasis on performing inversions, and called for improvements in models, including increased integration of verification data (observations). Current biospheric models vary widely in analysis of carbon levels at any given moment. Additionally, they lack sufficient verification data to capture anomalies accurately 24 hours/day and year-round, and to tell different fluxes apart within an analysis of varying carbon levels. Furthermore, country-level variations may not be detectable, and inversion results at smaller geographic areas (both 1-degree by 1-degree, and likely at many smaller country-level scales) are not verifiable.

Weir called for substantial improvements in process-based models to eliminate variability and improve sensitivity and results – and therefore improve the scientific community's ability to perform analysis of GHG mitigation activities. He specifically suggested improving terrestrial biospheric constraints to allow reliable attribution, and also a substantial expansion of development and integration of ground and sub-orbital verification data.

The discussion revolved around uncertainties in terrestrial biosphere modelling, and whether the main problem was in fact related to the models themselves or the (lack of) observations. There are currently unused (to some extent unavailable) atmospheric data that could improve models. It was observed that biosphere models are not always well benchmarked – it may be possible to use spatially explicit parameters to improve them. Other approaches to measure fluxes are under analysis, to be explored.

Surface-Based Observations

Alex Vermeulen, Integrated Carbon Observation System (ICOS), described ICOS, a state-of-the-art coordinated in-situ carbon cycle monitoring system, established in 2015, with 14 states joined as members to date. The 140 surface-based stations of ICOS are drawn from three larger networks – GAW (atmosphere), FLUXNET (land surface) and SOCAT (part of the GOOS oceans network). Together the ICOS stations serve as a reference network, providing fully traceable observations to Copernicus as well as generally on a free and open basis via a central data portal. Data is provided bi-annually at final quality, with daily NRT data for all major observables. Through Copernicus, ICOS data is integrated with MVS and the Global Stocktake. ICOS is also participating in EU innovation projects, seeking to help improve urban and ground-based remote sensing. Furthermore, it has also participated in developing a potential carbon observation network structure for Africa, of 12 stations, which would be distributed according to the gases prioritized.

Discussion noted that an output of this workshop could be building consensus on what kind of network/density would be needed for Africa, with the analysis driven by the assumption of coordination with top-down approaches and prioritizing their need for verification data, as recommended by earlier speakers.

Space Based Observations

David Crisp, Crisp Spectra, reviewed the state of the art in space-based observations of carbon dioxide and methane, concluding with a call to supplement current global activity with a comprehensive operational programme. He reviewed current capabilities of international satellites to measure carbon dioxide and methane averages and fluxes globally. He highlighted the increasing geographic specificity of averages, which is made possible by regular cross calibration with space and ground observations. Following up on the presentation by Brad Weir, he noted that the flux inversion models in fact are making good progress toward convergence with help from analyses by Weir and others. Other scientists are able to transform the results from biospheric models into reasonably robust flux estimates for at least the larger countries, and are currently providing, as pilot projects for the Global Stocktake, top-down, national carbon dioxide and methane budgets for multiple countries for use by the inventory agencies.

While tremendous progress has been made in the last 20 years in this young field, and new satellites are coming online with expanded capabilities, forward progress is hampered by the fact that currently most space-based observations of GHGs are being collected by scientific spacecraft with no operational infrastructure or mission continuity plans. An operational system based on user needs delivering an end-to-end product is needed to supplement the scientific activity. In addition, to resolve existing uncertainty regarding areas of highest GHG activity, namely the oceans, the tropics and high northern latitudes, a better surface-based (both ground and aircraft) system is needed to calibrate and validate space-based measurements.

The discussion touched on the added value of NWP assimilation as a tool to reduce key uncertainties. It also highlighted the CEOS Global Stocktake strategy, which recommends soliciting from the larger climate community with observation capability large-scale field studies to address priority geographic needs.

Additionally, participants considered how to maintain and stimulate scientific innovation when operationalizing satellite observations. It was suggested to follow the meteorological model and maintain in-house research arms within larger labs. This initiative was seen to have similarities to NWP in 1970s, in that it will include a big opportunity to learn and innovate.

Need for an Integrated Approach for Greenhouse Monitoring

Mark Dowell, Joint Research Centre, European Commission, prefaced his presentation by noting that many of the ideas being discussed in this workshop have come up in previous fora within both the space agencies and Copernicus, which helps underline the already existing broader consensus on the need for this work. He then drew from these fora to provide a series of suggestions on how to organize the GHG monitoring infrastructure.

Dowell reviewed the organizing principles for the Copernicus Carbon Initiative (CCI), described earlier in more detail by Peuch (Presentation 18, above). Initial principles for the CCI called for it to be fundamentally underpinned by strong user requirements based on international commitments and corresponding policy implementation; to emphasize systems (inventories, space-borne and in-situ observations, data assimilation framework, inversion system, transport models, decision support system); to emphasize operational intent from the outset, while still recognizing the need for continued R&D; and to acknowledge the fundamental added value of international engagement on system implementation/development.

Dowell noted that the UNFCCC timeline through 2028 for the first and second Global Stocktakes provides a clear timeframe for development of this new initiative, with opportunities for iterative improvement. The timeline of the Global Stocktake could help frame investments in infrastructure, satellites, etc.

He urged participants to refer in their future design activities to the 2018 CEOS Atmospheric Composition Virtual Constellation white paper, which involved some of this workshop's participants in defining a global architecture for monitoring atmospheric carbon and CH4 concentrations from instruments on space-based platforms. He noted that this proposed architecture has since been recognized by, among other documents, the WIGOS 2040 Vision and the SBSTA-51 (2019) conclusions (Paragraphs 35 and 40).

Dowell suggested that the core of the new global architecture may be comprised of modelling and data assimilation systems (likely several such systems at a global level – operated not just by countries with space programs). The systems would need to be designed to be responsive, so as modelling needs evolve over the decades ahead, they can respond. Given the strong policy needs at multiple levels (global, national and local) he urged the group to be careful when develop its messaging (on "why are we doing this?") and to think carefully on how bring together the broad stakeholder community. Co-development with the users is recommended. Satellite coordination is already reasonably well established across research and operational communities, but engaging with the data assimilation and modelling communities and the broader stakeholder group will need additional outreach and coordination.

IG3IS GHG/Carbon Monitoring Activities

Phil DeCola, University of Maryland, provided a briefing on the Integrated Global Greenhouse Gas Information System (IG3IS). IG3IS was inspired by basic measurements of atmospheric carbon and temperature showing the impacts and scientific basis for concern. DeCola recalled that already in 2008, the Committee on Atmospheric Science of WMO recommended that WMO work towards establishing an integrated global carbon observation, prediction and assessment programme aiming at operational implementation (October 2008 meeting, Recommendation 5). That turned into the original IG3IS. Its development was presaged by a shift in thinking at UNFCCC – understanding that layer of information coming from atmospheric composition elements can best help *improve* inventories, not police them – which opened the door for IG3IS to start providing systematic services for stakeholder communities looking to reduce their emissions. The focus of IG3IS has been national, urban, and on unexplored methane mitigation opportunities.

With regards to the proposals under discussion for a new global infrastructure, DeCola called for taking a multi-tiered platform approach, and cautioned that stakeholder/user coordination is essential, but that it requires hard work and active relationship-building.

GHG Monitoring in India

Vijay Soni, India Meteorological Department, presented information on India's carbon monitoring activities. For GHGs, large observational gaps exist over SE Asia; but it is known that India has a large, fast-growing economy and is emerging as a substantial GHG emitter. India has several institutions involved in GHG monitoring, starting from 1992. Such monitoring started on a project basis, without long-term commitment; but gradually has developed to support six sites for carbon flux measurements in the country.

WMO Role in the World Weather Watch

Anthony Rea, WMO Infrastructure Department, reviewed the original development, including the international context at the time, of the World Weather Watch programme (WWW) in the 1960s and 1970s, and discussed how it might serve as a role model for for the development today of a global GHG monitoring infrastructure. WWW was a visionary international initiative in the 1960s and 1970s that designed a multi-tiered system for global weather data. Initially it was comprised of three key systems: a Global Observing System for gathering observational data, a Global Telecommunications System for rapid exchange of data, and a Global Data-processing System for processing observational data and preparing forecasts.

WWW developed extremely rapidly in the six years after the first launch of satellites in 1957 due to support at the highest political levels by the most powerful nations of the world at that time (US and USSR). It has resulted in a dramatic improvement of forecast accuracy over time, and a levelling of disparities in quality between northern and southern hemispheres. Four main factors contributing to its success were a clear societal need, emerging technology and mature science, a clear vision for the future and a long-term plan, and political will at the national and international level. Given that the magnitude of the challenges around climate change mitigation today is similar, Rea urged participants and the larger community to think big and imagine what could be.

The discussion focused on how best to understand the role of oceans data in a GHG infrastructure, given that it has not been traditionally part of meteorological observations and that a great deal of ocean area is outside any national jurisdictions. However, participants were reminded that maritime weather was an early driver for international cooperation; even before WWW, countries established a system of weather ships in the northern hemisphere. Furthermore, ocean observation, ocean modelling and ocean-related services are now increasingly becoming integrated into WMO's activities: see for example the new WMO Unified Data Policy, which institutionalizes on an Earth system approach to international data exchange within the organization.

The participants also discussed how Meteorological Services in WWW operationalized the scientific competences that became central to the initiative; today the equivalent would involve shifting certain GHG-related activities from primarily research to an operational approach. Calls were made for simple and powerful visual ways to demonstrate progress on GHGs, as part of developing and justifying a new initiative.

GEO Perspectives

Yana Gevorgyan, GEO, noted that the value of this GHG monitoring infrastructure initiative will come when its data reach users/policymakers. This means that, to be successful, WMO must develop the initiative in an inclusive and partnership-oriented way. This should include include requisite links to other entities, notably ministries of environment and statistics, who provide the official reporting to UNFCCC, and non-governmental entities including private-sector finance, which are increasingly important roles as users of these types of data. GEO has a constituency comprised of these groups, and it thus sees its role as helping to ensure the appropriate and effective use of the results of this endeavour. GEO also can offer several relevant data products and services such as biosphere observations from AFOLU and blue carbon measurements.

GHG Integration Activities in Japan

Osamu Ochiai, JAXA, explained that Japan has a wide range of organizations involved in GHG satellite and ground observation networks, data analysis, modelling and research. He reiterated that establishing a means of collaboration among different national initiatives is essential for the success of proposed WMO initiative. As one such means of national collaboration, Ochiai described Japan's development of a concept for a central national platform, which acts as a coordination mechanism, and involves associated research projects, all aiming to facilitate interagency cooperation towards integrating these operational and research components.

At the COP-25 Japan Pavilion, Japan proposed developing such a central platform domestically and eluded on the idea of the international value of such a platform. The platform would share all data sources, analysis tools and model outputs as an integrated GHG system. Similar platforms if established by the other countries would collaborate with each other for products verification and comparison. As an outcome, the platform would provide data and knowledge to the UNFCCC, including the Global Stocktake, through various international bodies such as GEO, WMO, CEOS and the Global Carbon Project. To realize this platform concept, relevant activities are being promoted in Japan, little by little.

Key Recommendations and Way Forward

The following paragraphs present the overall conclusions and suggested way forward in narrative form. The summary slides containing recommendations to WMO that were introduced by the Facilitator and discussed and refined by all participants are available here.

Over the course of the discussions taking place during the first two days of the workshop, a common understanding emerged on the urgent need for a fully integrated, globally coordinated GHG observation monitoring initiative. Using the World Weather Watch as a paradigm, it would require close coordination with entities outside WMO with relevant expertise, learning lessons from the community's experience with the GEO Carbon Strategy. The initiative would encompass:

- Integrated observing systems, surface-based and space-based assets and activity data;
- Near-real time exchange of all observations (surface- and space-based);
- Multi-centre Earth system modelling and data assimilation systems;
- A tiered approach to modelling systems (spatially, temporally, in terms of coupling) including global and regional centres linked to national entities.

The discussion revealed broad agreement that this new initiative could as a primary purpose provide data and information (such as model output integrating all available observations) to the Parties to the UNFCCC. Other purposes may emerge. The Parties (governments) in turn would be able to use the information to plan, design and monitor the effectiveness of their mitigation steps. In this way it could function like the WWW, which provides global NWP products to national meteorological and hydrological services (NMHSs), who in turn use these products to provide services such as weather forecasts and warnings.

There was broad consensus that this initiative must leverage existing capabilities, seeking to accelerate and expand their scope. Furthermore, it needs to clearly articulate upfront how it builds upon and expands existing capabilities, as well as what it will provide and its benefits, particularly its benefits to the Parties to the UNFCCC. It needs to define services and information needs early in the process, and it will need to maintain continued engagement with the UNFCCC and other relevant stakeholders to ensure that it continues to respond to their needs. Development of the concept should be transparent to all potential stakeholders and participants.

As this initiative is urgently needed, immediate actions should be identified and taken, with the development of a long-term, stable, sustainable system proceeding in parallel. This urgency however must not precipitate unilateral action by WMO; detailed implementation and design should only follow after consensus emerges among the organizations and after engaging with stakeholders.

Among the high-priority issues that should be addressed within the overall initiative are:

- Promotion of the non-negotiable need to make all data openly available, including through timely delivery;

- Data harmonization and exchange, and benchmarking activities (both observation and model output);

- Interoperability, provision of standards, and protocols;

- Setting of quality standards for observations and model components;

- Compliance (data delivery) monitoring;

- Provision of pathways towards sustained funding for observing systems (e.g. GBON, SOFF);

- Provision of a roadmap for the coordination of the initiative;
- Early integration of stakeholders from developing countries.

The initiative should accommodate multiple timescales and scope of services relevant to daily, monthly, annual and decadal phenomena. It should support the Enhanced Transparency Framework (ETF) process in UNFCCC.

System Architecture

The overall system architecture should be designed:

- With the aim of improving our fundamental understanding of global biogeochemical cycles (carbon, CH_4, N_2O);
- With scope to intercompare products between service centres, as well as comparison/coherence of input data/models;
    - WMO to support systematic verification of products, and intercomparison of skills measures (cf NWP);
- To address the need for modelling systems consistent with a capability for reanalysis at different timescales, e.g. to perform:
    - Longer reanalysis back to least 1990 (emissions baseline);
    - Shorter reanalyses linking different GST cycles.

The system architecture should be developed with the understanding that priors provide an important link to the inventory community, serving as their direct contribution to the system when their products can be spatialized on thin regular grids.

Regarding satellite observations, existing coordination efforts such as CEOS and CGMS are invaluable and must be acknowledged. However, the system architecture will require an expansion upon currently planned capabilities towards a comprehensive space-based operational constellation.

Way Forward

As an immediate action, it was agreed that WMO should call for a round-table discussion with relevant parties to establish the need for a high-level coordination mechanism among all data providers. The round table should involve not only the Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP), but also external entities such as the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Oceanographic Commission of UNESCO (IOC), the United Nations Environment Programme (UNEP), the Food and Agriculture Organization of the United Nations (FAO), the Group on Earth Observations (GEO), the Committee on Earth Observation satellites (CEOS), the Coordination Group for Meteorological Satellites (CGMS), and the Intergovernmental Panel on Climate Change (IPCC), as well as relevant regional and national organizations (such as Copernicus). A comprehensive "landscape analysis" of roles and responsibilities in GHG monitoring should be undertaken, and GCOS should be invited to lead consideration of whether the Carbon Cycle observations set out in its latest Implementation Plan are comprehensive in terms of observational requirements for such an overall programme.

More broadly, parties should immediately act to:

- Seek to expand observing networks in priority regions including the tropics, the Southern Ocean and the Arctic;
- Establish collaboration between existing GHG modelling centres to provide access to common observational datasets and opportunities for intercomparison (lessons learned from NWP, Air-Quality forecasts, etc.);

- Initiate activities to support the current UNFCCC assessment cycle.

Going forward, in pursuing the new global initiative, the following steps were recommended:

- Clarify the requirements intended to be met by the initiative, including the primary target applications (e.g., large-scale distribution of anthropogenic fluxes, natural sources/sinks);
- Develop roadmap for design of comprehensive, integrated global GHG observing system consisting of both surface- and space-based assets, incorporating and building upon existing and already planned capabilities;
- Engage key organizations/entities performing GHG modelling and inversion activities (lessons learned from NWP centres and WGNE) and provide a framework for overall coordination and inclusiveness;
- Engage actively with stakeholders from developing countries; formulate capacity development activities - leveraging and coordinating ongoing activities GAW, GCOS, etc.;
- Develop pilot programs in two directions:
  - Early advanced users/countries;
  - Developing countries: use of new infrastructure applications aided by working with development agencies in the region;
- Develop a timeline for the establishment of the overall infrastructure.

Closing

Wenjian Zhang, WMO Assistant Secretary-General, closed the workshop, expressing appreciation and thanks to participants for their time and expert input. He noted that Members are facing challenging tasks ahead in work to manage and reduce carbon impacts, and that this group is playing an important role in supporting WMO to assist them.